Optical System Design OE5031 Final Project (Spring 2025) - Microscope Objective Design

YU-CHUN, LIN[1]

[1] *Department of Electrical Engineering, National Taiwan University, 2025 Taipei, Taiwan*
[*] *b10901151@ntu.edu.tw*

Abstract: This paper presents the final project for the Optical System Design course (OE5031) at National Taiwan University during Spring 2025. The objective of this project is to design and optimize a compact optical system while developing a deeper understanding of complex optical system operations. Detailed analysis is conducted to provide insight into the design process, which is essential for appreciating the complexity of common optical systems.

1. Introduction

As discussed in class, optical system design development can be viewed in two directions: micro-dimension and macro-dimension, corresponding to microscopes and telescopes, respectively. In Taiwan, an increasing number of studies are being conducted to advance microscopy technologies. Some developments even aim to achieve super-resolution that breaks the physical boundary of the diffraction limit, such as STED, SIM, and other techniques. Although not all of these advancements are purely optical, the optical system remains a critical component in the field of microscopy. Consequently, this report focuses on the simulation and analysis of microscope objectives using ZEMAX, with the goal of exploring the ingenious aspects of optical system design.

In this report, I will first define and introduce the system specifications. These parameters and requirements are established in advance to simulate real-world planning processes. Following the specifications, I will briefly describe the reference microscope design that served as my starting point. Then, I will thoroughly explain the optimization process and methodology that led to my final design. Finally, statistical and geometrical analyses will demonstrate the properties and advantages of my design compared to the prototype. The conclusion will summarize the content and results of this project.

Additionally, since this project was developed using Ansys Zemax OpticStudio Student edition, certain functionalities were unavailable, including non-sequential mode, find best asphere, design lockdown, and others. These limitations restricted some implementation options and adjustments, potentially constraining the system's performance. I highlight this issue in advance to help readers better understand certain design choices and procedures.

2. Initial Design Stage

2.1. System Specification

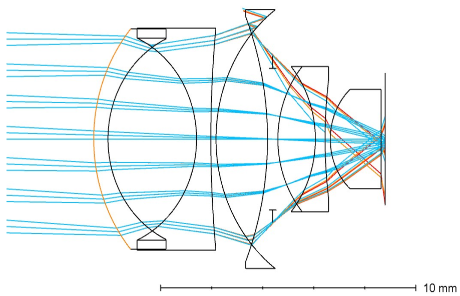
This design incorporates five system specifications: (i) The object distance to the first lens is 170 mm. (ii) The object is 16 mm in diameter. (iii) The system uses visible light (F, d, C lines). (iv) A diameter margin of 0.254 mm (0.01 inch) is included. (v) The magnification is -0.02. Note the negative sign in the magnification value.

In addition to these strict requirements, I adjusted variables to limit the physical length between the first surface and the image plane. While the TOTR merit function might seem appropriate for this purpose, I found it difficult to optimize even when experimenting with different weights. Therefore, I maintained the length as a variable while minimizing it while preserving performance.

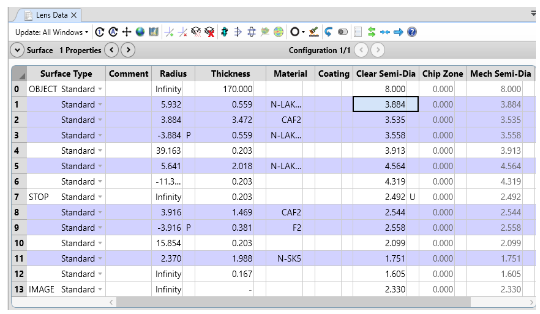
2.2. Design Prototype

Based on [1], I began my design with a prototype containing seven lenses. This design utilizes fewer lenses than general patented designs such as [2], which typically use eight or even more lenses [3]. Although [2] stated that at least five components are needed for a microscope objective to function properly, additional lenses are commonly employed to achieve higher quality.

After setting up global parameters in System Explorer and performing a simple quick focus, the results are depicted in Fig. 1, showing the lens prototype (a) and the lens data (b) with conditioning. Different colors in (a) represent different wavelengths in the visible light spectrum.



(a) Design Layout



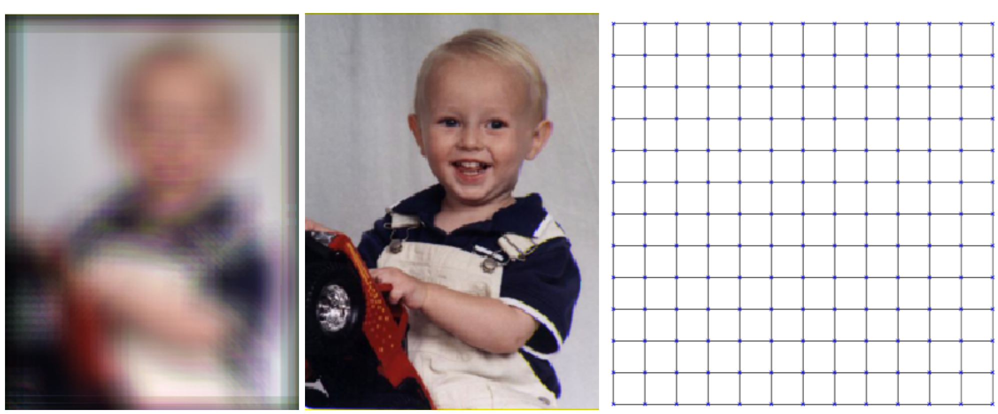
		Surface Type	Comment	Radius		Thickness	Material	Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia
0	OBJECT	Standard		Infinity		170.000			8.000		0.000	8.000
1		Standard		5.932		0.559	N-LAK...		3.884		0.000	3.884
2		Standard		3.884		3.472	CAF2		3.535		0.000	3.535
3		Standard		-3.884	P	0.559	N-LAK...		3.558		0.000	3.558
4		Standard		39.163		0.203			3.913		0.000	3.913
5		Standard		5.641		2.018	N-LAK...		4.564		0.000	4.564
6		Standard		-11.3...		0.203			4.319		0.000	4.319
7	STOP	Standard		Infinity		0.203			2.492	U	0.000	2.492
8		Standard		3.916		1.469	CAF2		2.544		0.000	2.544
9		Standard		-3.916	P	0.381	F2		2.558		0.000	2.558
10		Standard		15.854		0.203			2.099		0.000	2.099
11		Standard		2.370		1.988	N-SK5		1.751		0.000	1.751
12		Standard		Infinity		0.167			1.605		0.000	1.605
13	IMAGE	Standard		Infinity		-			2.330		0.000	2.330

(b) Lens Data

Fig. 1. Prototype Microscope Objective Design (reference: [1])

It is evident that several lenses in this initial design would be difficult to manufacture, and dominant aberrations significantly reduce resolution. Visualized ray tracing reveals several unwanted optical paths leading to poor imaging. To improve the prototype, it is important to first analyze the current design thoroughly.

2.3. Prototype System Analysis



(a) With geometric aberration (b) Without geometric aberration (c) Grid Distortion Analysis

Fig. 2. Imaging Simulation on Alex200.bmp with and without geometric aberration in ZEMAX & Distortion Analysis

To assess the system, I began by identifying the dominant aberrations. The visual comparison in Fig. 2 between images (a) and (b) clearly demonstrates that geometric aberrations are the

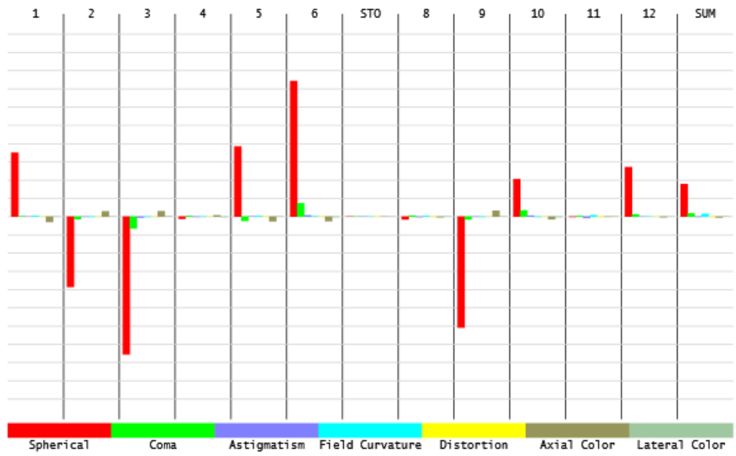


Fig. 3. Seidel Diagram of the prototype system

primary issue. Note that the images are actually upside down; I rotated them manually for clearer demonstration. This finding is further supported by the grid distortion plot in (c), which shows that distortion has minimal effect on the system. Additionally, the vignetting plot (not visualized in this report, but appearing as a horizontal line with amplitude 1) indicates that the prototype imaging system adequately addresses vignetting and distortion. The prototype design also performs satisfactorily regarding chromatic aberration, as the Ray Fan shows good alignment among the three wavelengths.

For a more detailed analysis, I plotted the Seidel Diagram to monitor each aberration's contribution to the imaging quality. As depicted in Fig. 3, spherical aberration is the most significant problem requiring attention, while focusing on minimizing the point spread function to approach the diffraction limit as closely as possible. Additionally, chromatic aberration is present in this design; although less severe than spherical aberration, it still limits some design options when attempting to achieve diffraction-limited imaging in this microscope objective.

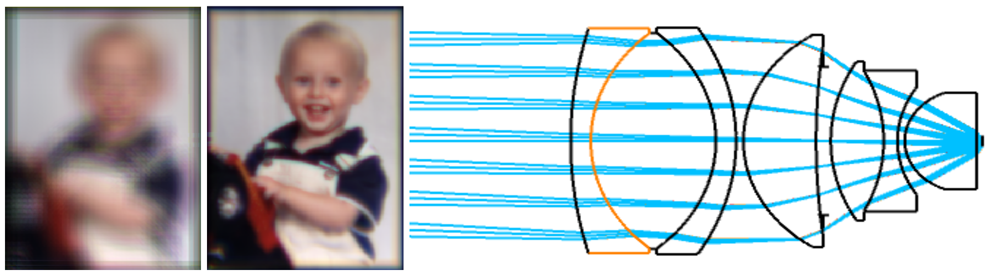
By examining Fig. 3, we can compare aberrations across different surfaces. Higher aberration ratios occur in lenses closer to the object. The positive and negative effects of spherical aberration also vary in magnitude, as observed in the SUM column of the figure. To address this issue, I aimed to compensate for aberrations in lenses closer to the object through adjustments to lenses closer to the image plane. With accumulated aberration on lenses near the image plane, I then explored aspherical surfaces and different glass materials to develop a comprehensive optimization solution for the entire optical system.

3. System Design Optimization

3.1. Coarse Local Optimization - Radius, Clear Semi-Diameter, Thickness

To improve the design, I began by directly setting radius, clear semi-diameter, and thickness as variables. Running optimization significantly decreased the merit function loss. However, this straightforward optimization process resulted in an excessively elongated physical system. As mentioned earlier, using the TOTR merit function proved ineffective, as it compromised several positive attributes of the prototype design, such as low chromatic aberration and the short distance between the first surface and image plane.

I adopted an approach of establishing pickup values with references to other surfaces. This stabilized local optimization and produced more promising results within our specifications and preferences. During this process, conic constant modification and glass material selection were not yet included. Additional merit functions such as PMAG, REAX, REAY, and RSCE were used to maintain desired optimization results. The PMAG function was particularly critical for meeting the requirement of Magnification = -0.02. The corresponding weights for these operations were initially set to 1 at this stage. However, as discovered later, these weights were adjusted during the fine-tuning stage to achieve the final result.



(a) Before Optimization (b) After Optimization (c) Design Layout

Fig. 4. System Design Layout and Image Simulation on Alex200.bmp with geometric aberration after coarse local optimization

Fig. 4 illustrates the clear improvement between the before and after optimization states. As shown in (c), the design layout is much more feasible for manufacturing compared to the prototype design with its several unusual lenses. However, the optical system still exhibits problems, particularly at the intersection of the 5th and 6th lenses. The vertically straight edge could present significant manufacturing difficulties. To ensure the microscope objective can be produced, further modifications to these structural elements were necessary.

3.2. *Manufacturability Check*

The manufacturing difficulties mentioned above primarily stem from mismatches between the lenses' clear semi-diameters and incompatibilities between mechanical semi-diameters. I manually smoothed out these inconsistencies among surfaces using pickup settings. Additionally, in the system explorer, I specified the aperture type as "Float By Stop Size" with a 0.254 mm clear semi-diameter margin.

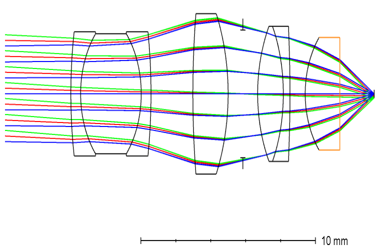
3.3. *Advanced Hammer Optimization*

After completing the manufacturability check and establishing pickup values, I employed hammer optimization for global enhancement. During this process, all glass materials were set as variables to achieve convergence toward the minimum. To attain decent resolution with minimal aberration, aspherical surfaces were also considered. With the limitations of Ansys Zemax OpticStudio Student edition, I was restricted to using hammer optimization for approximately one minute, without access to the "Find Best Asphere" function. Through trial and error, I achieved a desirable result by incorporating the conic constants of the 9th and 11th surfaces into the hammer optimization process. This choice was influenced by Professor Guo-Dung Su's lecture, which emphasized that aspherical surfaces are typically utilized in the "back" of an optical system to compensate for the accumulated effects of previous lenses.

3.4. *Fine-tuning the System*

Although hammer optimization sometimes generates designs with extremely low loss values, these may not always align with our desired outcomes. As mentioned, to achieve the final result of TOTR = 17.3731, I did not rely solely on setting numerous merit functions and optimizing through

ZEMAX. Without sufficient requirements and accurate weights, relying entirely on ZEMAX can lead to unexpected defects. My approach involved first fixing promising parameters and then verifying their feasibility after optimization. While this iterative procedure would be time-consuming if starting from scratch, I applied it only in the final stages, requiring approximately one hour. In my opinion, a potential future development could involve automatically selecting variables from all parameters based on certain prompts, possibly utilizing reinforcement learning or large language models.



(a) Design Layout

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	170.000			8.000	0.000	8.000	0.000	0.000
1	(aper) Standard		15.718 V	0.559	SPINEL S		2.426	0.000	2.426	0.000	-
2	(aper) Standard		3.640 V	3.472	KCL S		2.343	0.000	2.343	0.000	-
3	(aper) Standard		-3.640 P	0.559	N-LAS... S		2.343 P	0.000	2.343	0.000	-
4	(aper) Standard		-16.7... V	2.399 V			2.426 P	0.000	2.426	0.000	0.000
5	Standard		28.436 V	2.018	LAF2 S		3.131	0.000	3.131	0.000	-
6	Standard		-7.546 V	0.846 V			3.131 P	0.000	3.131	0.000	0.000
7	STOP Standard		Infinity	0.846 P			2.492 U	0.000	2.492	0.000	0.000
8	Standard		5.700 V	1.469	SRF2 S		2.639	0.000	2.639	0.000	-
9	(aper) Standard		-6.085 V	0.381	SF57 S		2.639 P	0.000	2.639	0.533 V	-
10	Standard		-39.1... V	0.873			2.474	0.000	2.474	0.000	0.000
11	Standard		3.412 V	1.988	N-PSK53 S		2.199	0.000	2.199	-0.073 V	-
12	Standard		Infinity	1.963			1.702	0.000	1.702	0.000	0.000
13	IMAGE Standard		Infinity	-			0.162	0.000	0.162	0.000	0.000

(b) Lens Data

Fig. 5. Optimized Microscope Objective Design

In Fig. 5, image (a) shows the resultant optical system without manufacturability issues. Rays from different object heights all converge successfully, meeting all requirements. The microscope objective's length remains reasonably compact. Image (b) displays the lens data information, including pickup and variable settings. Note the two non-zero conic constants that play crucial roles in this design.

4. Results and Analysis

(a) Initial Stage (b) After 1st Optimization (c) Final Result (d) No Geometric Aberration

Fig. 6. Imaging Simulation on Alex200.bmp with geometric aberration & without geometric aberration in ZEMAX

As shown in Fig. 6, we can observe the progressive improvement in image quality from the initial prototype stage through coarse optimization to the final result. Image (d) displays the simulation with no geometric aberration for comparison, and my final result (c) is visually quite similar to this ideal case. The resolution of my final design achieves high quality, preserving image

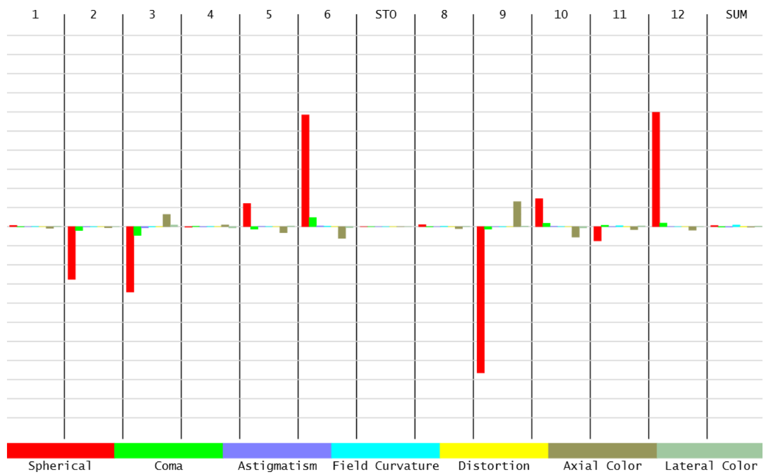
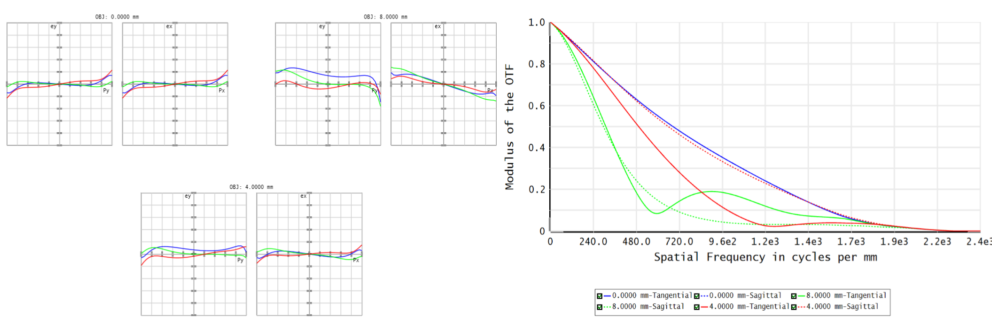


Fig. 7. Seidel Diagram of Final Design

details and sharpness. This comparison clearly demonstrates that the approaches implemented at each stage provided significant improvements to the system, confirming that these combined methods effectively produce clear imaging.

In addition to visual improvements, the optimized system offers enhanced robustness against aberrations. The Seidel Diagram in Fig. 7 reveals a significant reduction of aberrations in the SUM column, with minimal residual aberrations. This highlights the benefits of incorporating aspherical surfaces, as mentioned in the design optimization procedure. By selecting just two lenses to be aspherical, I was able to compensate for most aberration issues through the optimization process.



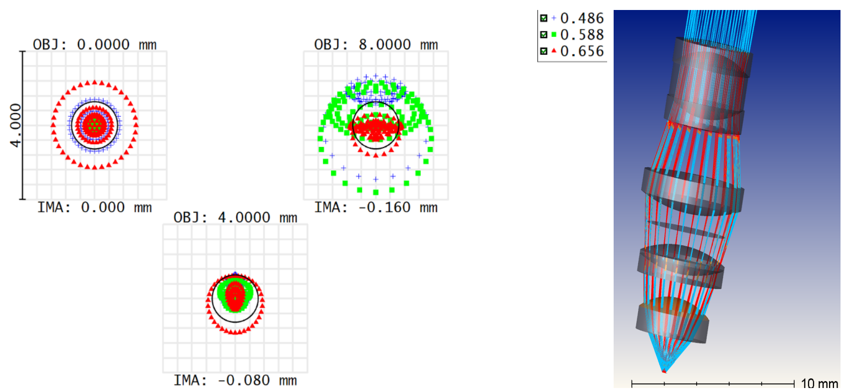
(a) Ray Fan

(b) FFT MTF

Fig. 8. Ray Fan & FFT MTF of Final Design

While achromatic aberrations are critical issues that must be addressed in optical system design, chromatic aberration also requires careful attention. The Ray Fan diagram in Fig. 8(a) displays chromatic aberration conditions at different object heights (view angles). These results can be categorized into two groups. For object heights of 0 and 4 millimeters, the three wavelengths behave similarly, with relatively small deviations from the x-axis. The ray fans in both x and y dimensions exhibit generally similar patterns. Although moderate gaps between wavelengths can be observed at the extremes of the x-axis, this performance is still acceptable considering both chromatic and achromatic aberrations. However, for larger object heights (up to 8 millimeters), chromatic aberration becomes more pronounced. Secondary axial chromatic aberration may further diminish performance, as indicated by the ray fan. Additionally, the x and y patterns show insufficient similarity, with red and green lines exhibiting vertical shifts and slight distortion. The blue line also changes notably. This suggests that accommodating a wider field of view would require further system modifications or dependence on the specific type of microscope system. This presents an opportunity for future optimization work.

Regarding the FFT MTF plot shown in Fig. 8(b), both tangential and sagittal lines with 0 millimeter object height perform excellently, closely resembling the optimal Modulation Transfer Function. Surprisingly, the sagittal line with 4 millimeter object height demonstrates similar performance to these well-behaved lines. However, the remaining lines cannot achieve such favorable MTF values, as they are affected by sinc components in their representation functions. This indicates larger focusing errors in these cases, causing their MTF to decrease more rapidly than the three near-oblique straight lines.



(a) Spot Diagram

(b) Shaded Model

Fig. 9. Spot Diagram & Shaded Model of Final Design

Fig. 9(a) presents the spot diagram with the Airy disk circle indicated in black. The scale for these graphs is 4 micrometers, with an Airy disk radius of 0.639 micrometers. Ideally, an optical system's spot diagram should achieve the size of the Airy disk. My design approaches this physical limitation, with spot sizes of the same order of magnitude as the Airy disk and only a few times larger. This indicates promising results for the optimized system, approaching the physical limitation. The statistical results of the spot diagram are as follows:

Table 1. Spot Diagram Text Information

Field	1	2	3
OBJ (mm)	0.000	4.000	8.000
RMS Radius	0.471	0.908	0.405
GEO Radius	1.149	1.810	0.929

Comparing the information in Table 1 with the Airy disk radius of 0.639μm, we can conclude that the system approaches optimal performance. Although further compensation for persistent aberrations could be achieved by adding more lenses to the current system, it is generally preferable to minimize the number of lenses in an optical system. Regarding the implementation of additional aspherical surfaces, after testing various combinations without the assistance of the "Find Best Asphere" function, the RMS radius and GEO radius could not be reduced further. Thus, the design converged to a local minimum that likely approximates the global minimum given the constraints and limitations of this project.

Fig. 9(b) displays the shaded model of the final design with 50% opacity for clearer visualization. The scale bar at the bottom illustrates the reasonable size of the developed microscope objective.

5. Conclusion

In this final project, I began with a microscope objective prototype system from [1]. Through coarse local optimization, hammer global optimization, and extensive fine-tuning, I developed a final design whose spot diagram dimensions are comparable to the Airy disk. Various analytical diagrams provide comprehensive assessment of the design, confirming its robustness and high quality. The initial observations and analysis of the prototype imaging system informed many of my optimization decisions and serve as an effective comparison point for evaluating the final optical system.

Although this work presents a well-optimized result, there remains room for further improvement. Potential enhancements include: reducing all spots to fit within the Airy disk, achieving better FFT MTF performance, or implementing non-sequential mode with tolerance functions (unavailable in the student version).

I look forward to further optimizing this design and integrating it with other microscope components to build a complete simulated microscope. While this will present a significant challenge, it offers an excellent opportunity to apply the knowledge gained in this course. I hope this work will serve as a valuable practice exercise and reference for others and myself. I extend my gratitude to everyone who assisted me with this project.

References

1. K.Norton, “Designing a Microscope Objective with OpticStudio.” https://www.youtube.com/watch?v=gPOn0qOxgz4
2. M. Matsubara, “Objective lens systems for use in microscopes.” https://patents.google.com/patent/US3925910A/en
3. K, Zhang, “Optical system design of double-sided telecentric microscope with high numerical aperture and long working distance.” https://opg.optica.org/oe/fulltext.cfm?uri=oe-31-14-23518&id=532354